Supporting Information

Heatwaves and gradual warming differentially alter freshwater fish biodiversity and functional structure

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SUPPLEMENTARY TABLE

Supplementary Table 1 References of the datasets used in the study. Source ID corresponds to the ID from the RivFishTIME database (Comte et al., 2021), and the Source name aligns with the Origin name as defined by Danet et al. (2024).

Source ID	Source name	Country	No of sites	Reference
4	Balaton	HUN	24	Erős, T., Sály, P., Takács, P., Higgins, C. L., Bíró, P., & Schmera, D. (2013). Quantifying temporal variability in the metacommunity structure of stream fishes: the influence of non-native species and environmental drivers. Hydrobiologia, 722, 31-43.
7	Finland	FIN	207	Finnish electrofishing register Hertta (2019). Available at https://wwwp2.ymparisto.fi/koekalastus_sahko/ [Accessed on 04/11/2023].
8	Forillon	CAN	2	Sigouin, D. (2017). Fish Communities - Forillon, dataset fe2441a6-8ae4-4884-b181-cd7ec53bd842. Available at https://open.canada.ca/data/en/dataset/fe2441a6-8ae4-4884-b181 cd7ec53bd842 [Accessed on 05/07/2019].
15	Iowa	USA	36	Iowa DNR [Department of Natural Resources] (2013) BioNet - Iowa DNR Biological Monitoring and Assessment Database. Available at https://programs.iowadnr.gov/bionet/ [Accessedon02/01/2018].
22	Matthews	USA	2	Matthews, W.J. & Marsh-Matthews, E. (2017) Data from: Stream fish community dynamics: a critical synthesis, Dryad, Dataset, doi: 10.5061/dryad.2435k.
24	Minnesota	USA	8	Minnesota Pollution Control Agency (2018) Surface water data. Available at https://webapp.pca.state.mn.us/surface-water [Accessedon04/11/2023].
25	Montana	USA	35	Montana, Fish, Wildlife & Parks (2019) Fish Survey Sites. Available at http://gis mtfwp.opendata.arcgis.com/datasets/8192e75218c6460ba97ba3dd0a2fb3a5 [Accessedon05/21/2019].
26	NAWQA	USA	60	U.S. Geological Survey (2019) BioData-Aquatic Bioassessment Data for the Nation. Available at https://apps.usgs.gov/biodata/ [Accessedon25/05/2023], doi:10.5066/F77W698B.

27	NFPD	GBR	747	U.K. Environmental Agency (2019) National Fish Populations Database (NFPD): Freshwater fish survey relational datasets. Available at https://data.gov.uk/dataset/d129b21c-9e59-4913-91d2-82faef1862dd/nfpd freshwater-fish-survey-relational-datasets [Accessedon10/15/2019].
32	Onema	BEL	2	Office français de la biodiversité (2019) Suivi des éléments biologiques ‘POISSONS’ des rivières françaises. Available at http://www.naiades.eaufrance.fr/acces-donnees#/hydrobiologie [Accessed on 07/08/2019].
32	Onema	ESP	1	Office français de la biodiversité (2019) Suivi des éléments biologiques ‘POISSONS’ des rivières françaises. Available at http://www.naiades.eaufrance.fr/acces-donnees#/hydrobiologie [Accessed on 07/08/2019].
32	Onema	FRA	687	Office français de la biodiversité (2019) Suivi des éléments biologiques ‘POISSONS’ des rivières françaises. Available at http://www.naiades.eaufrance.fr/acces-donnees#/hydrobiologie [Accessed on 07/08/2019].
34	PaisVasco	ESP	93	Agencia Vasca del Agua (2019) UBEGI. Información sobre el estado de las masas de agua de la CAPV. Available at http://www.uragentzia.euskadi.eus/informacion/ubegi/u81-0003341/es/ [Accessed 10/10/2019].
39	RWMP	CAN	6	Toronto and Region Conservation Authority (TRCA) (2018) Watershed Fish Community. Available at https://data.trca.ca/dataset/2018-watershed-fish-community [Accessed on 09/18/2019].
42	SERS	FIN	11	Sers, B. (2013) Swedish Electrofishing RegiSter - SERS. Swedish University of Agricultural Sciences (SLU), Department of Aquatic Resources. Available at http://www.slu.se/elfiskeregistret [Accessed on 11/18/2019].
42	SERS	NOR	2	Sers, B. (2013) Swedish Electrofishing RegiSter - SERS. Swedish University of Agricultural Sciences (SLU), Department of Aquatic Resources. Available at http://www.slu.se/elfiskeregistret [Accessed on 11/18/2019].
42	SERS	SWE	1663	Sers, B. (2013) Swedish Electrofishing RegiSter - SERS. Swedish University of Agricultural Sciences (SLU), Department of Aquatic Resources. Available at http://www.slu.se/elfiskeregistret [Accessed on 11/18/2019].

43	Tordera	ESP	9	Benejam, L., Angermeier, P.L., Munné, A. & García-Berthou, E. (2010) Assessing effects of water abstraction on fish assemblages in Mediterranean streams. Freshwater Biology 55, 628–642. Merciai, R., Molons-Sierra, C., Sabater, S. & García-Berthou, E. (2017) Water abstraction affects abundance, size-structure and growth of two threatened cyprinid fishes. Plos One, 12, e0175932.
MARIS	MARIS	USA	135	U.S. Geological Survey, Core Science Analytics and Synthesis Program, 20131201, Multistate Aquatic Resources Information System (MARIS): United States Geological Survey, https://doi.org/10.5066/F7988525.
Maryland	Maryland	USA	26	Montgomery county monitoring program (2018). Available at https://www.montgomerycountymd.gov/water/streams/data.html
Ohio	Ohio	USA	42	Ohio statewide monitoring program (2018). Available at https://www.orsanco.org/programs/fish-population/
RAMP	RAMP	CAN	15	Regional Aquatics Monitoring Program (2018). Available at http://www.ramp-alberta.org/RAMP.aspx
Tennessee	Tennessee	USA	9	Danet, A., Giam, X., Olden, J. D., & Comte, L. (2024). Past and recent anthropogenic pressures drive rapid changes in riverine fish communities. Nature Ecology & Evolution, 8, 442–453.

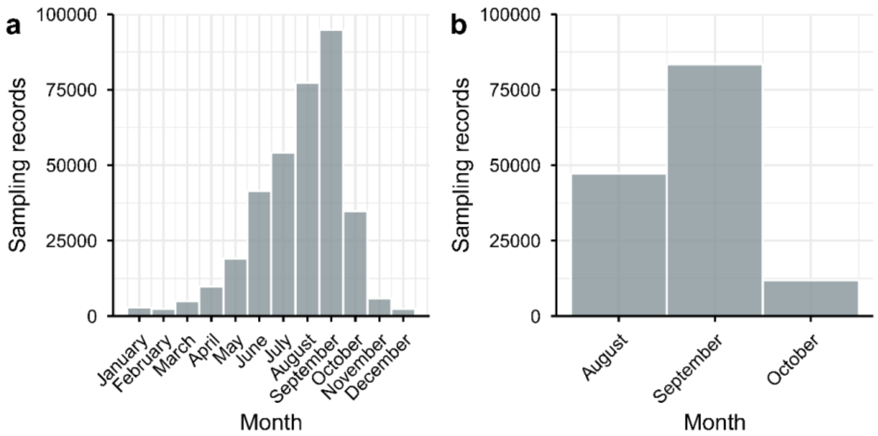
Supplementary Table 2 Estimated effects of heatwave intensity and annual warming on native and non-native species richness across continents and climate zones derived from generalized linear mixed models (GLMMs). Correspond to Fig. 2 in the main text.

Variable	Response	Continent/Climate	Estimate	SE	DF	T statistic	*P*-value
Heatwave intensity	Native richness	Americas	0.0476	0.0260	21119	1.8342	0.0666
		Europe	-0.0103	0.0072	21119	-1.4372	0.1507
		Cold	0.0037	0.0118	21119	0.3112	0.7557
		Temperate	-0.0121	0.0086	21119	-1.4142	0.1573
	Non-native richness	Americas	-0.0098	0.0260	21119	-0.3772	0.7060
		Europe	0.0025	0.0072	21119	0.3440	0.7308
		Cold	0.0030	0.0118	21119	0.2543	0.7993
		Temperate	0.0016	0.0086	21119	0.1923	0.8475
Annual warming	Native richness	Americas	0.0290	0.0241	21119	1.2026	0.2292
		Europe	0.0412	0.0072	21119	5.7032	***P*<0.001**
		Cold	0.0547	0.0141	21119	3.8674	***P*<0.001**
		Temperate	0.0362	0.0079	21119	4.5571	***P*<0.001**
	Non-native richness	Americas	0.0818	0.0241	21119	3.3930	***P*<0.001**
		Europe	0.0209	0.0072	21119	2.8890	***P*<0.01**
		Cold	0.0286	0.0141	21119	2.0213	***P*<0.05**
		Temperate	0.0251	0.0079	21119	3.1674	***P*<0.01**

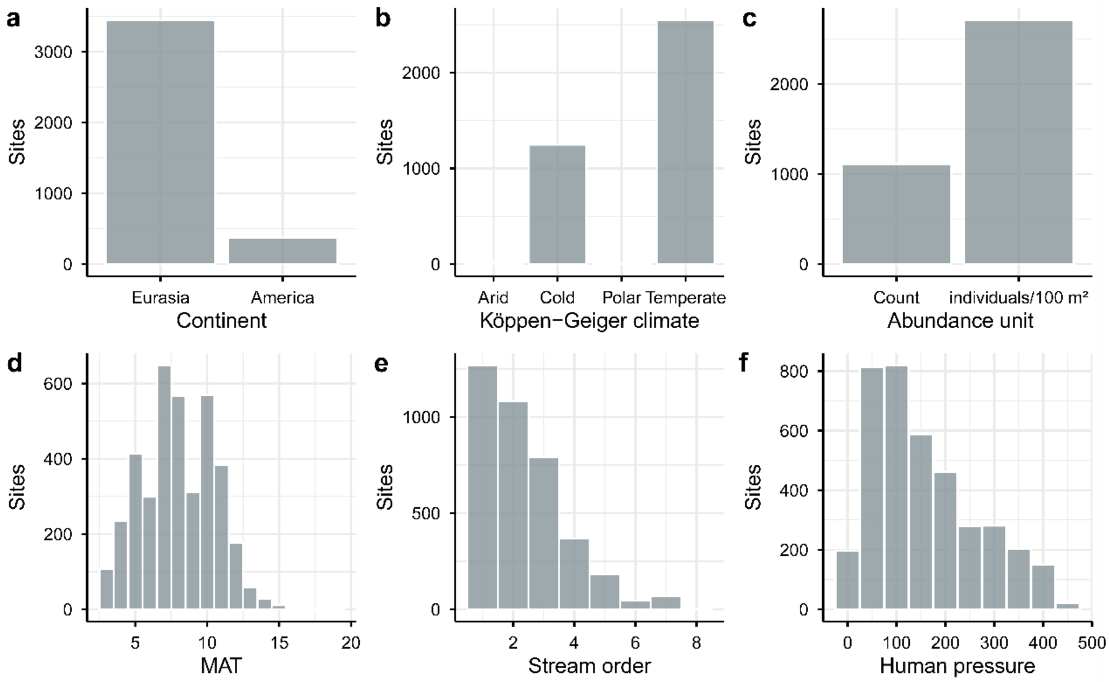
Supplementary Table 3 Pairwise comparisons of the effects (slopes) of heatwave intensity and annual warming on native and non-native species richness across continents and climate zones. Pairwise differences were tested based on estimated marginal trends from the same GLMMs.

Variable	Response	Contrast	Estimate	SE	DF	T statistic	P-value
Heatwave intensity	Native richness	Americas - Europe	0.0580	0.0270	21119	2.1510	***P*****<0.05**
		Cold - Temperate	0.0158	0.0146	21119	1.0834	0.2787
	Non-native richness	Americas - Europe	-0.0123	0.0270	21119	-0.4553	0.6489
		Cold - Temperate	0.0014	0.0146	21119	0.0926	0.9262
Annual warming	Native richness	Americas - Europe	-0.0122	0.0252	21119	-0.4867	0.6265
		Cold - Temperate	0.0185	0.0162	21119	1.1418	0.2535
	Non-native richness	Americas - Europe	0.0609	0.0252	21119	2.4198	***P*****<0.05**
		Cold - Temperate	0.0034	0.0162	21119	0.2121	0.8320

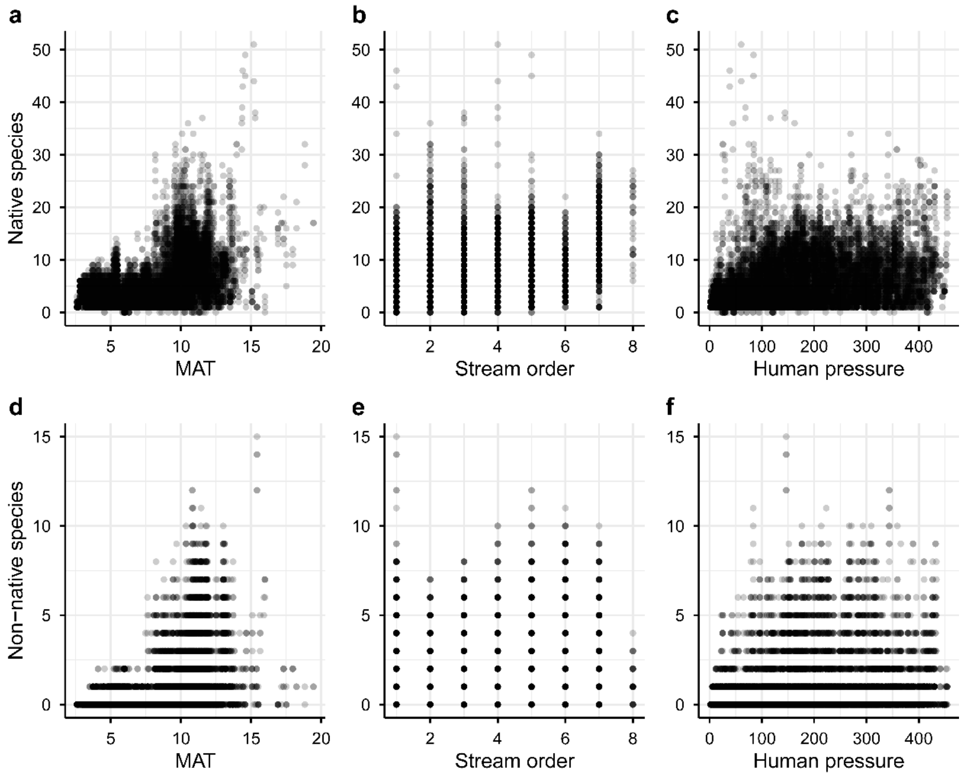
SUPPLEMENTARY FIGURES



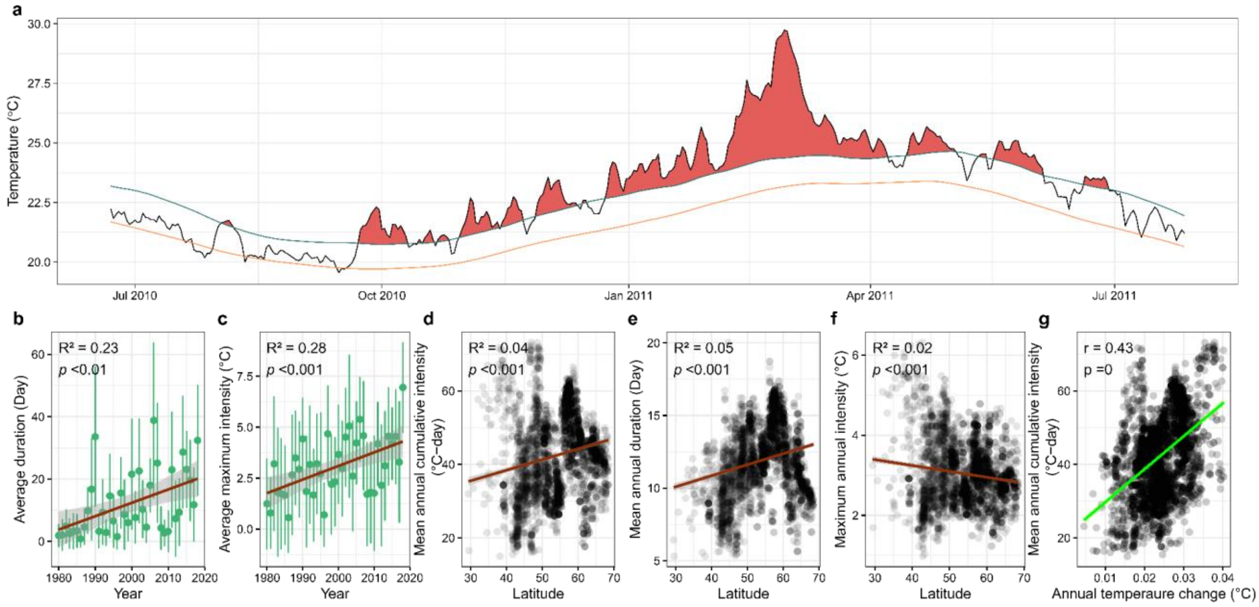
Supplementary Fig. 1 Monthly distribution of sampling events (a) before and (b) after data filtering.



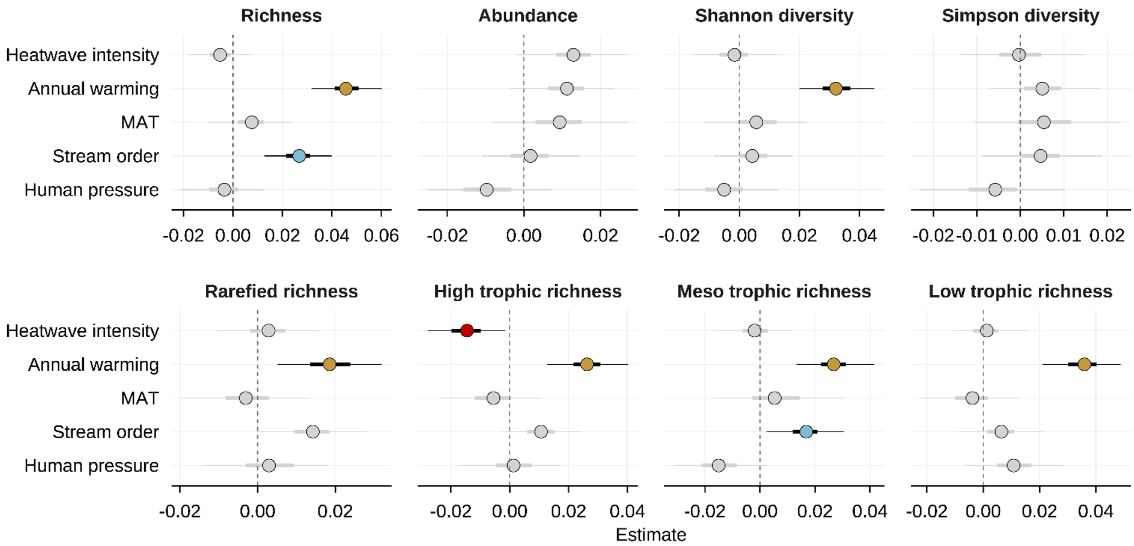
Supplementary Fig. 2 Distribution of sampling sites (time series) by (a) continent, (b) climate zones, (c) abundance units (by count or individual density), (d) mean annual temperature (MAT), (e) stream order, and (f) human pressure.



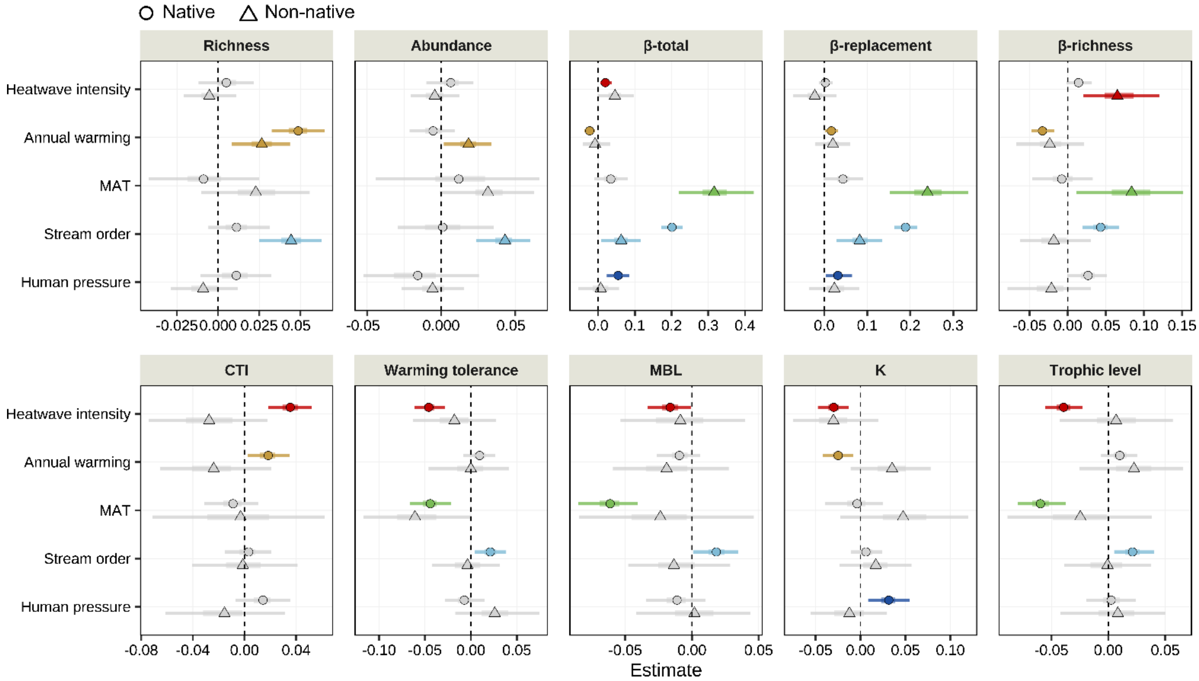
Supplementary Fig. 3 Species richness of (a–c) native and (d–f) non-native species captured in individual sampling events along MAT, stream order, and human pressure gradients.



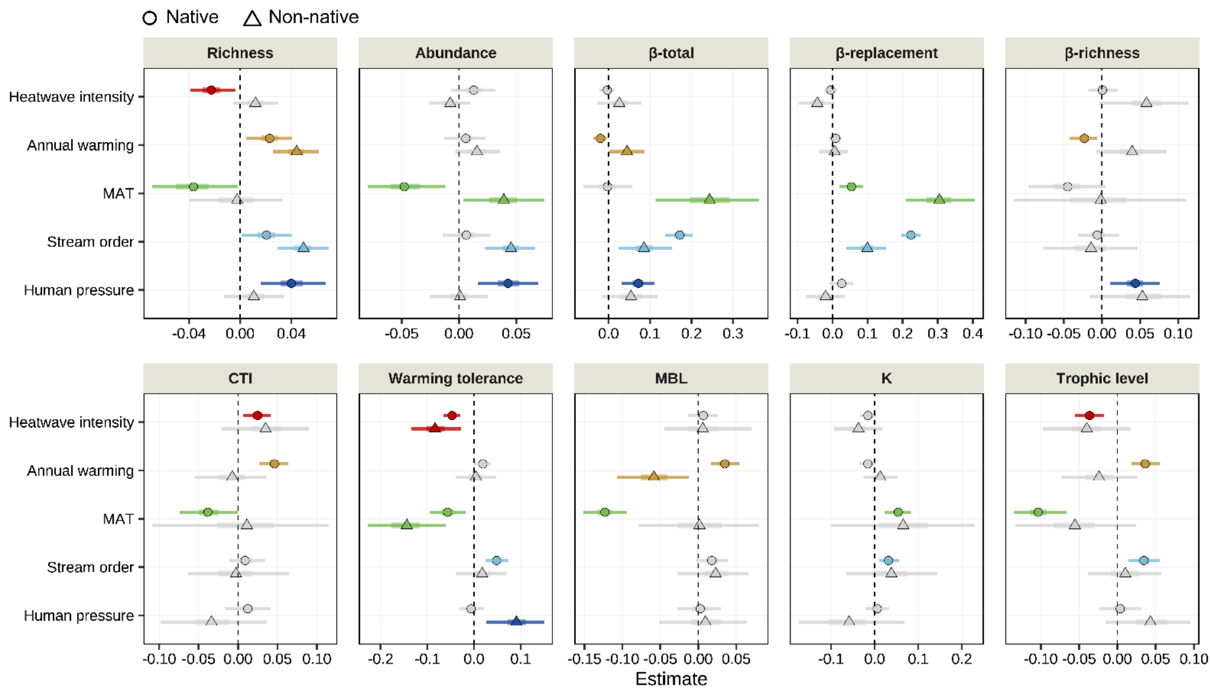
Supplementary Fig. 4 (a) Schematic illustration of the heatwave calculation. The orange line represents the climatological seasonal cycle, while the black line represents daily temperatures. The green line indicates the seasonal cycle daily threshold (e.g., 95th percentile). The red areas above the threshold temperature are considered heatwaves. The relationship between (b) heatwave duration and (c) heatwave maximum intensity and year. The green circles represent the heatwave metrics averaged across sites (n = 3,822) of each calendar year. Error bars refer to standard deviation. The relationship between (d) annual cumulative intensity, (e) heatwave duration, and (f) heatwave maximum intensity and latitude. The gray circles represent the mean annual values of the heatwave metrics over 1980–2018 at each site. (g) The Pearson correlation between mean annual heatwave cumulative intensity and temperature change across sites over 1980–2018.



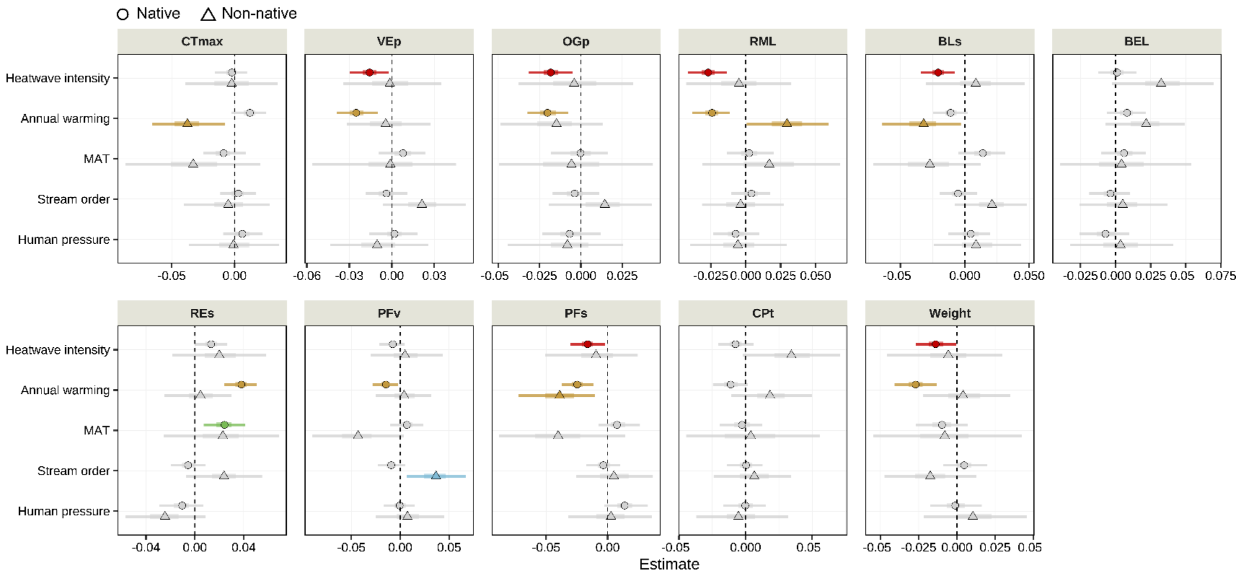
Supplementary Fig. 5 The effects of heatwave intensity, annual warming, MAT, stream order, and human pressure on changes in Shannon diversity, Simpson diversity, rarefied richness, and richness of three trophic levels of all fishes. The horizontal bars with error bars represent the median and the 50% and 95% confidence intervals; gray symbols represent confidence intervals that span zero.



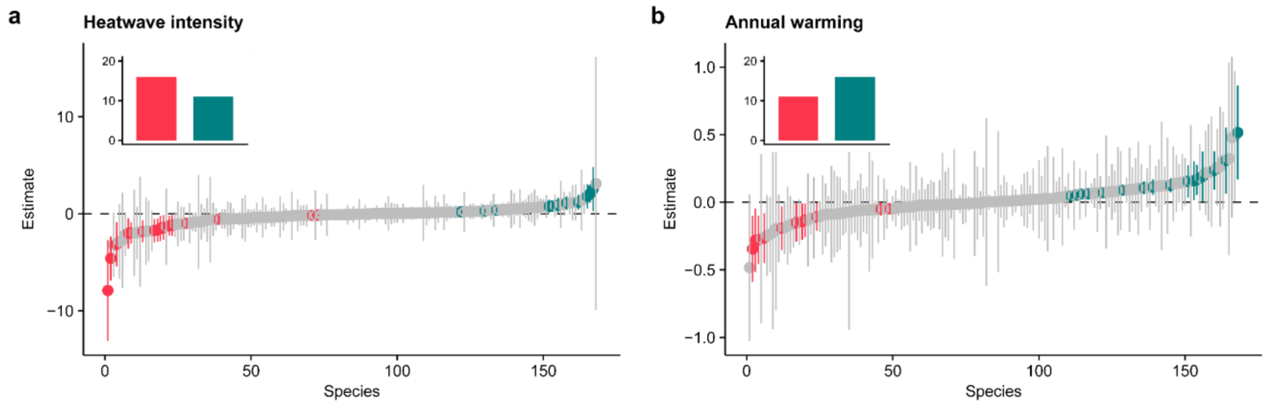
Supplementary Fig. 6 The effects of heatwave intensity, annual warming, mean annual temperature (MAT), stream order, and human pressure over a three-year interval. Estimated effect sizes are shown for species richness, abundance, β-diversity and its components (β-replacement and β-richness), and on assemblage mean functional traits (community temperature index [CTI], warming tolerance, maximum body length [MBL], growth rate [K], trophic level, and species richness at three trophic levels) of native and non-native species. The horizontal bars with error bars represent the median and the 50% and 95% confidence intervals; gray symbols represent confidence intervals that span zero.



Supplementary Fig. 7 The effects of heatwave intensity, annual warming, mean annual temperature (MAT), stream order, and human pressure over a five-year interval. Estimated effect sizes are shown for species richness, abundance, β-diversity and its components (β-replacement and β-richness), and on assemblage mean functional traits (community temperature index [CTI], warming tolerance, maximum body length [MBL], growth rate [K], trophic level, and species richness at three trophic levels) of native and non-native species. The horizontal bars with error bars represent the median and the 50% and 95% confidence intervals; gray symbols represent confidence intervals that span zero.



Supplementary Fig. 8 The effects of heatwave intensity, annual warming, mean annual temperature (MAT), stream order, and human pressure on assemblage mean critical thermal maximum (CT_{max}), vertical eye position (VEp), oral gape position (OGp), relative maxillary length (RML), body lateral shape (BLs), body elongation (BEL), relative eye size (REs), pectoral fin vertical position (PFv), pectoral fin size (PFs), caudal peduncle throttling (CPt), and weight of native and non-native species. The horizontal bars with error bars represent the median and the 50% and 95% confidence intervals; gray symbols represent confidence intervals that span zero.



Supplementary Fig. 9 Response of species (≥20 observations, n = 168) abundances to (a) heatwave intensity and (b) annual warming. Each dot represents a fish species. Error bars show 95% confidence intervals. Red, teal, and gray dots represent significant negative, significant positive, and non-significant responses, respectively. Results are ordered according to the estimated effect size. The inset shows the number of species with positive and negative responses.

References

Comte, L., J. Carvajal-Quintero, P. A. Tedesco, X. Giam, U. Brose, T. Eros, A. F. Filipe, et al. 2021. RivFishTIME: A global database of fish time-series to study global change ecology in riverine systems. *Global Ecology and Biogeography* **30**:38-50.

Danet, A., X. Giam, J. D. Olden, and L. Comte. 2024. Past and recent anthropogenic pressures drive rapid changes in riverine fish communities. *Nature Ecology & Evolution* **8**:442–453.